



# An innovative method based on satellite image analysis to check fault in a PV system lead–acid battery



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## ABSTRACT

Batteries are an important part in photovoltaic systems. They ensure reliability and good operation of the overall PV system. In this paper, we proposed a method based on the estimation of the solar radiation to check the faults that occur in the lead–acid batteries. At first, the GISTEL (Gisement solaire par télédétection: Solar Radiation by Teledetection) model is chosen as a satellite image approach to estimate the hourly global solar radiation. Secondly, the estimated data are selected as input to check the faults of the lead–acid battery. A simple and effective method is developed to detect the internal resistance effect as well as the overcharging problem during the charging and discharging cycles. The experimental results show the easiness of the proposed method that possesses a good accuracy.

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## 1. Introduction

The growing demand of energy in our life requires renewable solutions apart from the limited fossil energies. In addition, the negative effect of the traditional sources of energy that polluted the atmosphere leads us to search new environment-friendly solutions such as solar and wind energy. Solar energy is more and more used to generate electricity by converting solar radiation into useful DC power using PV panels. Nevertheless, the efficiency of panels is considered low due to financial and technical problems [16]. Hence, the optimal monitoring of PV systems is needed that depend strongly on the estimated solar radiation and checking the failures in the devices of PV systems such as panels, batteries and converters. In this view, we proceeded to study the effect of the losses in batteries to ensure the optimal operation of PV systems. For that, the estimation of solar radiation is considered to be an essential part in the PV system monitoring. Different methods were proposed in the literature to estimate the solar radiation data such as ground models [2,10,6] or the satellite images processing approaches [3,13,17]. Nevertheless, ground models are not effective because of the lack of the measured solar radiation. Hence, we have chosen in this paper the satellite methods due to their performances and accuracy. The GISTEL (Gisement solaire par télédétection) model is one of the most succeeded satellite methods to extract the solar radiation [18,15]. The first version of the GISTEL model was developed by Cano et al. [7]. The satellite images used in the GISTEL model provide an estimation of the solar radiation for any location around the world. The advantages of the GISTEL model are that it depends only on the satellite images and some parameters such as longitude, latitude and link turbidity. In addition, the

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good operation of the batteries represents a very important task in the PV system monitoring [12,11,22]. Moreover, a periodical check of the state of the batteries, especially the lead–acid ones, can give information about the operation state of the PV systems. On the other hand, the results from the models to estimate the solar radiation are complex and require a lot of calculation time. Different methods were presented in literature to monitor the losses in PV system batteries. McKenna et al. [14] have studied the economic and environmental impact of the use of lead–acid batteries in grid-connected PV systems. Tsang and Chan [20] have explained the equivalent DC resistances of Lithium ion battery cells of several health conditions during charging mode under different temperatures and they have established the relationships between the equivalent DC resistance, health condition and operating temperature. However, those papers have studied the SOC of the battery without taking into consideration the solar radiation as an important input. Moreover, they presented complicated methods to detect faults in PV systems.

For these reasons, we propose, firstly, the GISTEL methodology improved by fuzzy logic technic as a satellite images approach to estimate the amount of the solar radiation. The GISTEL model is a physical approach that used real visible images to extract the solar radiation. These data have an important effect on the output of PV systems; a good estimation of the solar radiation data leads to an efficient PV system.

Secondly, the monitoring of the lead–acid solar battery requires to check it and to identify the failures in real-time. In this paper, we have chosen to test the effect of the battery internal resistance and the overcharging case in the floating diet. The variation of the internal resistance of the battery has negative impacts in the PV system efficiency as well as in the battery lifetime.

Hence, in this work, we intend to show the effects of an increase of the internal resistance and of the degradation of the storage unit capacity through the introduction of the battery internal resistance. Moreover, the second effect to be checked is the overcharging of the battery and its effects on the PV system performances as an overcharging cause a decrease of the water level in the lead–acid battery which results into degradation of the internal plates of the battery. In this study, the method is not developed to supervise PV plants, just small stand-alone applications where the cost of communications, as well as electronics for the measurements is not justified.

The follow up of this paper is organized as follows. Section 2 presents a background of the GISTEL model. In Section 3, we show the methodology used in this work to check the failures in PV system battery. In Section 4, we have simulated the results obtained from the GISTEL model and compared them to the measured solar radiation data. Moreover, the simulated results of the proposed approach in the case of the absence of failure in the PV system battery have been also carried out. The last section is devoted to the conclusion and discussion of future work.

## 2. Methodology

The identification of losses in PV systems presents a big task to achieve the desired output. For that, we are interested in detecting failures in the storage unit that causes a decrease in the efficiency of the PV system [9]. In this work, a proposed simulation method based on the Matlab/Simulink environment has been used to detect the faults in the batteries. The GISTEL method was first applied for the estimation of solar radiation data, based on the extracted satellite images. Secondly, these data were introduced into the PV array to produce the output power. After that, this energy was stored in batteries to ensure the autonomy of the PV system. The third stage consists in studying the behavior of the storage unit under different situations. The proposed structure presented in Fig. 1.

### 2.1. GISTEL model

In the previous paper by the authors of this study [18] the GISTEL model is defined as a satellite methodology based on a simple physical model. It is used to estimate global solar irradiance from METEOSAT data. The adopted methodology has several steps that we have summarized in the diagram of Fig. 2.

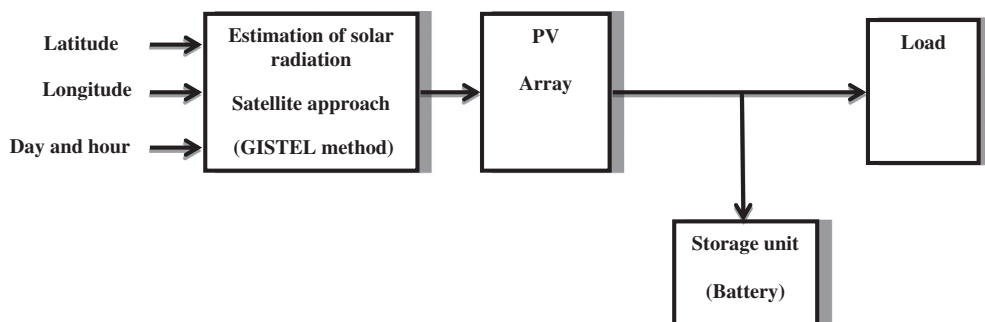


Fig. 1. Flowchart of the proposed methodology.

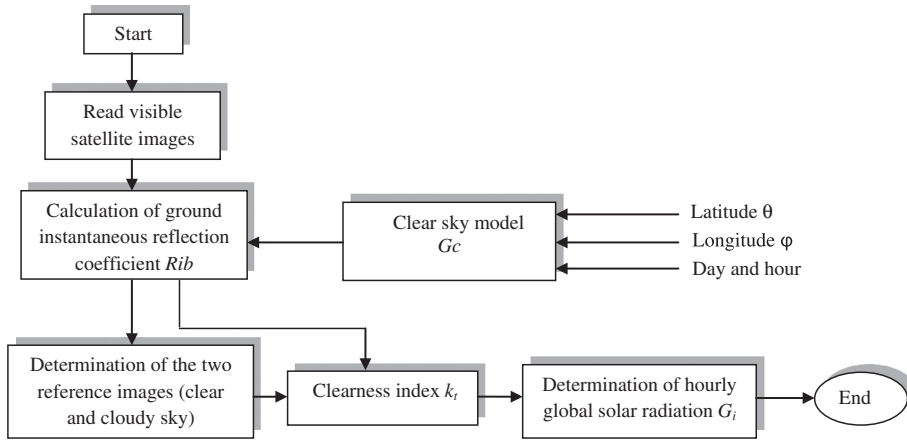


Fig. 2. The different steps of the GISTEL model.

1. To estimate the global solar radiation ( $G_c$ ) under a clear sky, the world organization of meteorology (W.M.O.) [21] model given by Eq. (1) is used; this model depends on the solar height ( $h_s$ ) and the linked turbidity factor ( $T_L$ ) used to quantify the effect of atmospheric components of solar radiation, the  $T_L$  values generally vary from 2 (very pure and dry sky) to 6 (polluted and humid sky).

$$G_c = cor[1300 - 57T_L](\sin(h_s))^{(36+T_L)/33} \quad (1)$$

where  $cor$  is the correction factor of the earth–sun distance given by Eq. (2) and  $n_j$  is the number of the days of the year.

$$cor = 1 + 0.034 \cos(0.986(n_j - 3)) \quad (2)$$

2. The ground instantaneous reflection coefficients  $Rib(x, y, d, h)$  for each pixel  $(x, y)$  of the visible MSG image of the day  $d$  and the hour  $h$  are given by Eq. (3). Those coefficients represent the reflection of solar radiation on the surface.

$$Rib(x, y, d, h) = \frac{Bi(x, y, d, h) - Bia(x, y, d, h)}{K \cdot G_c(x, y, d, h) \cdot Ti(x, y, d, h)} \quad (3)$$

where  $Bi(x, y, d, h)$  represents the brightness of the  $(x, y)$  pixel,  $Bia(x, y, d, h)$  the atmospheric brightness recorded by the satellite above the sea by a clear sky. This brightness was considered constant, and it is equal to 12 [4];  $K$  is the factor calibration of the visible channel sensor equal to 0.514.  $Ti(x, y, d, h)$  is the transmission coefficient of the direct irradiation from the ground to the satellite. It is given by Eq. (4),

$$Ti = \frac{(1390 - 31T_L)}{1367} \exp \left[ -\frac{T_L}{12.6 \sin(h_v + 2)} \right] \quad (4)$$

where  $h_v$  is the height angle of the satellite, given by Eq. (5).

$$h_v = \arcsin \left( \frac{1.862 \cos(\varphi) \cos(\theta) - 0.274}{\sqrt{3.41 - \cos(\varphi) \cos(\theta)}} \right) \quad (5)$$

$\theta$  and  $\varphi$  are respectively the latitude and the longitude.

3. To determine the two clear and cloudy reference images, a sequence of images was taken over a long period at 12 h UTC. Taking the minimum values of the reflection coefficients obtained from those sequence images, the clear sky reference image can be obtained. On the other hand, the cloudy sky reference image is constructed by using the greatest values of the reflection coefficient obtained using the same sequence of images.
4. The clearness index  $k_t$  is calculated for each image by comparing pixel by pixel and hour by hour the instantaneous reflection coefficients  $Rib$  with the two clear sky  $R_c$  and the cloudy sky  $R_n$  reflection coefficients. According to this comparison three types of skies can be observed namely clear sky, partially covered sky and completely covered sky [4], as expressed in Eq. (6).

$$\begin{aligned} &\bullet \text{ Clear sky : } Rib \leq R_c : k_t = 1 \\ &\bullet \text{ Partially covered sky : } R_c < Rib < R_n : k_t = 1 - (1 - K_0) \frac{(Rib - R_c)}{(R_n - R_c)} \\ &\bullet \text{ Completely covered sky : } Rib \geq R_n : k_t = K_0 \end{aligned} \quad (6)$$

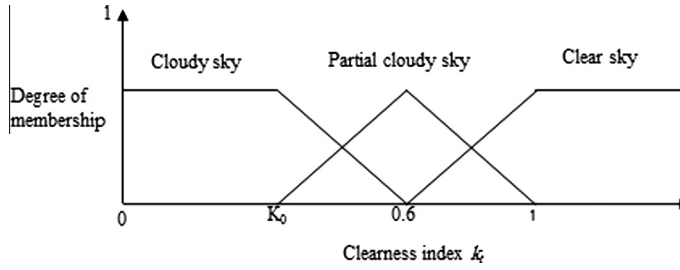


Fig. 3. Fuzzy logic membership functions.

where  $K_0$  is the index by a cloudy sky equals to 0.2. However, for obtaining more precise results a fuzzy logic approach is proposed in this paper. Fuzzy logic methodology has the ability to translate human qualitative knowledge into formal algorithms; it deals with reasoning that is approximate rather than fixed. It consists of using expert rules that can sometimes produce a simple set of control for a dynamical system with less effort. Hence, three rules are introduced in this work to obtain logical values of the clearness index  $k_t$  as expressed in Fig. 3.

5. Finally the instantaneous global solar radiation  $G_i(x, y, d, h)$  for each pixel is obtained by multiplying the clearness index  $k_t$  by the global solar radiation obtained under clear sky  $G_c(x, y, d, h)$ . As expressed in Eq. (7) as

$$G_i(x, y, d, h) = k_t \times G_c(x, y, d, h) \quad (7)$$

### 3. PV system modeling

#### 3.1. Modeling of PV array

To obtain the DC output powers, the output current and voltage of the PV array has been calculated using a double diode PV model as expressed in Eq. (8) [1,8].

$$I = I_{ph} - I_{01} \left( \exp \left( \frac{V + R_s I}{n_1 V_t} - 1 \right) \right) - I_{02} \left( \exp \left( \frac{V + R_s I}{n_2 V_t} - 1 \right) \right) - \frac{V + R_s I}{R_{sh}} \quad (8)$$

where  $I_{ph}$  is the current generated by the incident light.  $I_{01}$ ,  $I_{02}$  are the reverse saturation currents of the diodes D1 and D2 respectively.  $V_t$  is the thermal voltage.  $n_1$ ,  $n_2$  are the ideality factors of diodes D1 and D2.  $R_s$  and  $R_{sh}$  are the series and shunt resistance respectively.  $V$  and  $I$  are the output PV module voltage and current respectively.

#### 3.2. Storage unit model

The battery used in this work is a lead acid battery with 12 V of voltage and 104 A h of capacity; it is expressed by the following equation [19]:

Charge model ( $i^* < 0$ ):

$$f(it, i^*, i, Exp) = E_0 - K \frac{Q}{it - 0.1Q} i^* - K \frac{Q}{Q - it} it + Laplace^{-1} \left( \frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s} \right) \quad (9)$$

Discharge model ( $i^* > 0$ ):

$$f(it, i^*, i, Exp) = E_0 - K \frac{Q}{Q - it} i^* - K \frac{Q}{Q - it} it + Laplace^{-1} \left( \frac{Exp(s)}{Sel(s)} \cdot 0 \right) \quad (10)$$

where  $E_0$  is the constant voltage (V);  $Exp(s)$  is the exponential zone dynamics (V);  $Sel(s)$  represents the battery mode.  $Sel(s) = 1$  during battery charging,  $Sel(s) = 0$  during battery discharge;  $K$  is the polarization resistance (Ohm);  $i^*$  is the low frequency current dynamic (A);  $i$  is the battery current (A);  $it$  is the extracted capacity (A h);  $Q$  is the maximum battery capacity (A h).

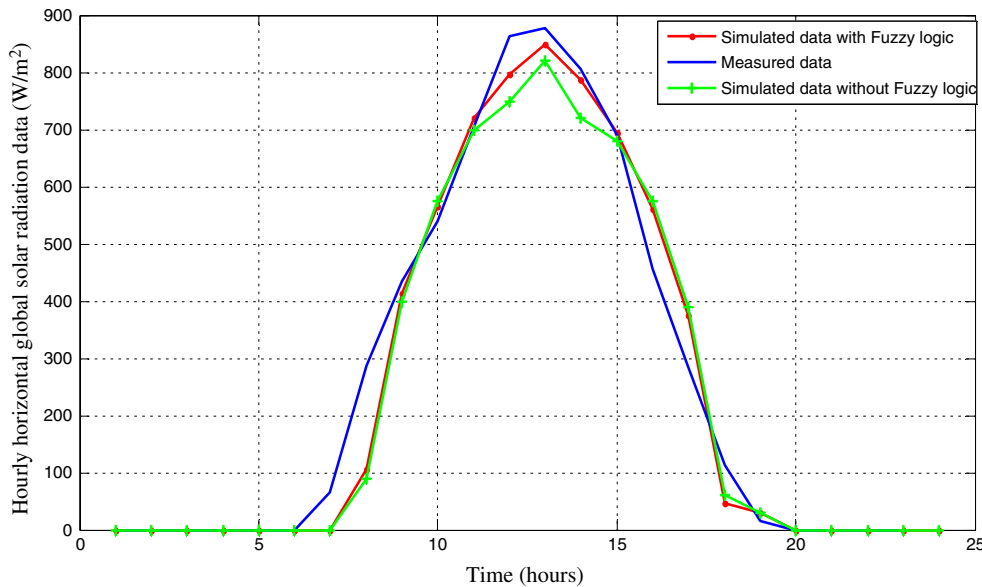
### 4. Simulation results and discussion

The objective of this work is the identification of faults in the PV system battery. For that, we used in the simulation a PV system with four panels (two panels in series with two branches) that represent a 300 Wp as total output power. The characteristics of the PV panels are given in Table 1. The objective is the extraction of the solar radiation data via satellite images using GISTEL model and use this data for the identification of failure in the battery that allowed minimizing the losses in the PV system.

**Table 1**

The solar panel parameters.

| Parameters                   | Values  |
|------------------------------|---------|
| Maximum power (Pmax)         | 75 W    |
| Maximum power voltage (Vmpp) | 21.68 V |
| Maximum power current (Impp) | 3.33 A  |
| Open circuit voltage (Voc)   | 21.40 V |
| Short circuit current (Isc)  | 3.69 A  |
| Max system voltage           | 1000 V  |



**Fig. 4.** Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 3rd March 2013 for the site of Bouzereah, Algeria.

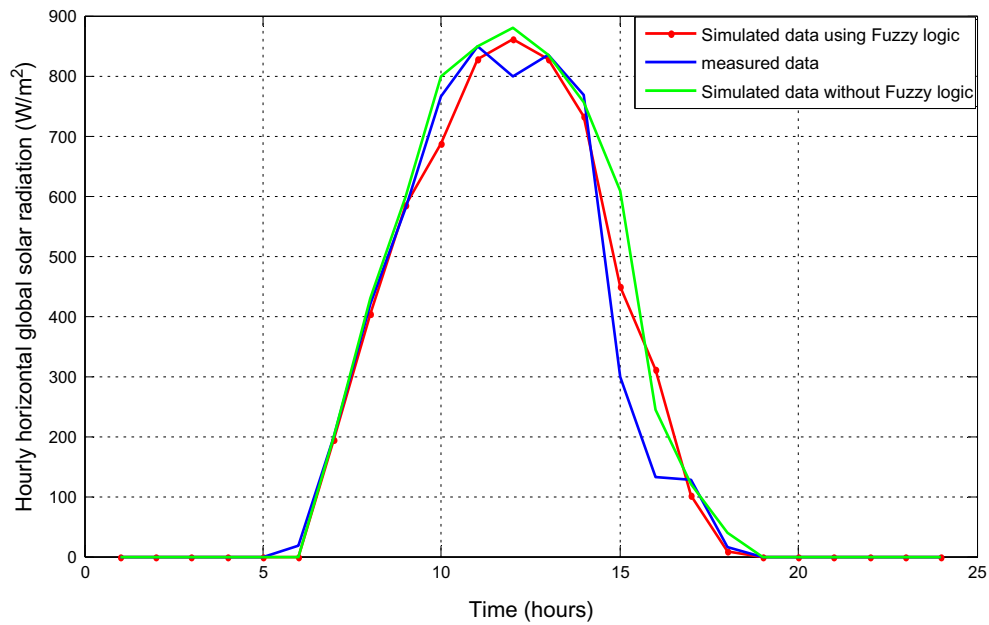
In the first step, the satellite approach (GISTEL model) was improved using the fuzzy logic method. The obtained data from GISTEL model using FL and without FL were compared with the measured data. For the validation purpose, we have chosen three locations. First, in Algeria (Bouzereah 36.78°N, 3°E) for the days of 3rd of February 2013 and the 26th of February 2013 and (Ghardaia 32.48°N, 3.66°E) for the days of 22nd November 2012 and the 7th of December 2012; the data were collected from the National Meteorological Office (ONM) of Algeria. The third location is Almeria in Spain (36.84°N, 2.4°W) the data were collected from the GeoModel Solar S.R.O., M. Marecka 3, Bratislava, Slovakia for the days of 15th February 2011 and the 20th February 2011. Moreover, the satellite images for each hour were obtained from the Meteo Company B.V website: (<http://www.sat24.com>) for all locations of Bouzereah and Ghardaia in Algeria and Almeria in Spain.

The simulation results are shown in Figs. 4–9 that represents the hourly global horizontal solar radiation time series for the three locations; the blue<sup>3</sup> line represents the measured data, the red dot line indicate the simulation data improved by FL (fuzzy logic) technic and the green dot one presents the simulated data without FL method. The RMSE and NRMSE were used to give a value for our validation. Eqs. (11) and (12) represent the RMSE and NRMSE respectively [5]:

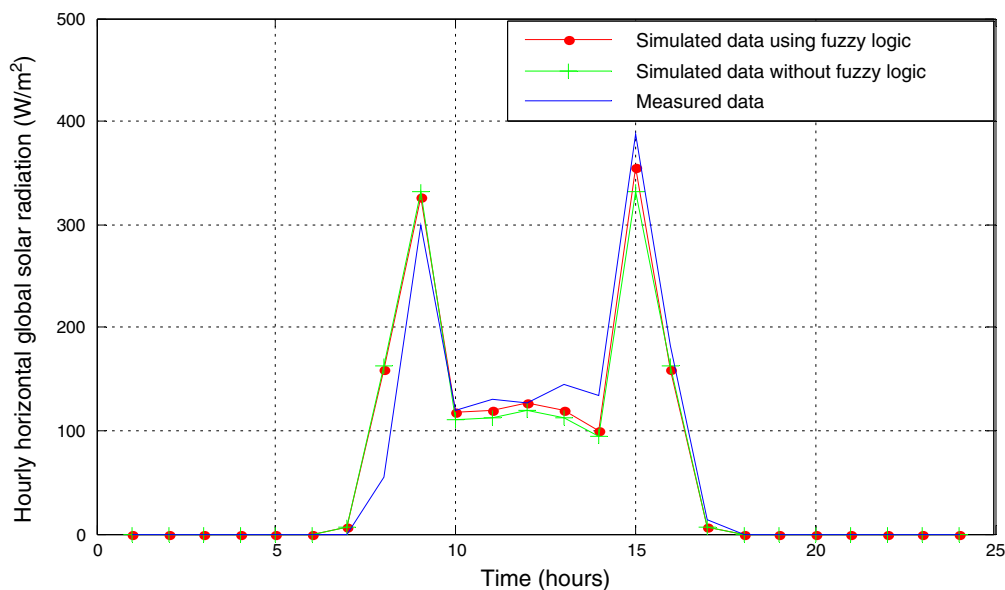
$$RMSE = \left[ \frac{1}{n} \sum_{i=1}^n (I_{i,predicted} - I_{i,measured})^2 \right]^{\frac{1}{2}} \quad (11)$$

$$NRMSE = \left( \frac{\left[ \frac{1}{n} \sum_{i=1}^n (I_{i,predicted} - I_{i,measured})^2 \right]^{\frac{1}{2}}}{\frac{1}{n} \sum_{i=1}^n (I_{i,measured})} \right) \quad (12)$$

<sup>3</sup> For interpretation of color in Figs. 4–9 and 12–15, the reader is referred to the web version of this article.



**Fig. 5.** Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 26th March 2013 for the site of Bouzerah, Algeria.

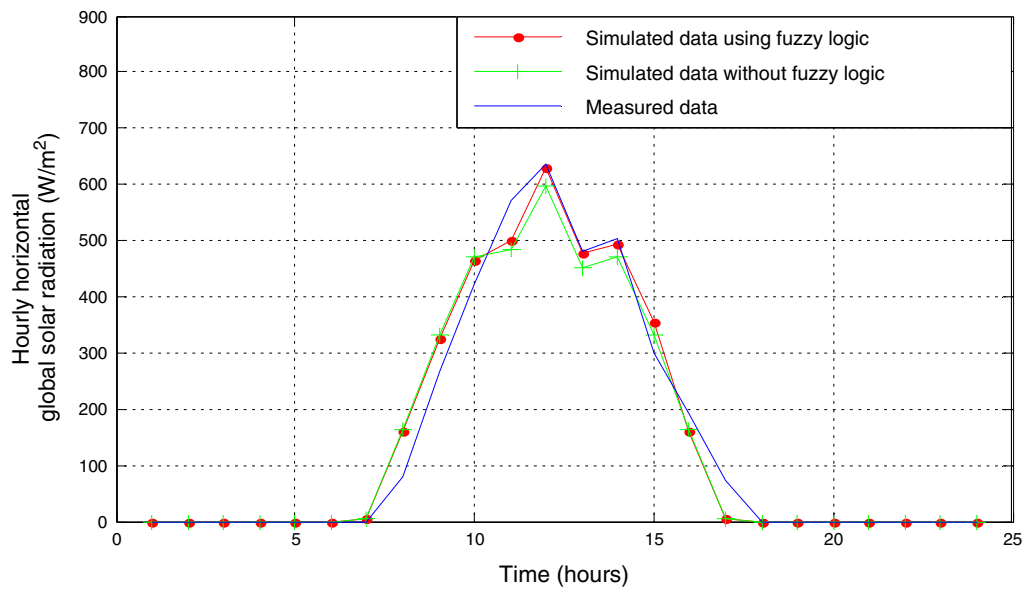


**Fig. 6.** Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 22nd November 2012 for the site of Ghardaia, Algeria.

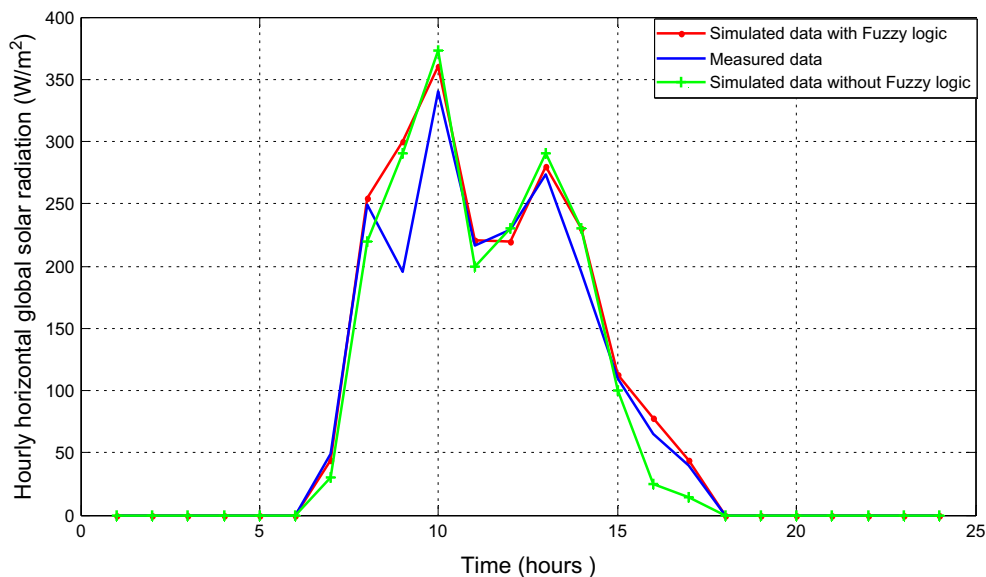
In Figs. 4–9, we observed that the simulation solar radiation data are changed from low values in sunrise and sunset to high ones at noon. The simulation of hourly solar radiation using FL is almost the same as the measured data. Moreover; the occurrence of fluctuations indicates the passage of clouds.

Table 1 represents the RMSE and the NRMSE error of simulation results with and without FL technic for the three locations.

From Table 2, the simulation results of GISTEL model with FL represent good values of an NRMSE error between 0.2 and 0.28 comparing with the measured solar radiation data and the estimation without FL for all locations. For that, the GISTEL model with fuzzy logic method represents a good improvement for the estimation of hourly horizontal global solar radiation by satellite images.



**Fig. 7.** Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 7th December 2012 for the site of Ghardaia, Algeria.

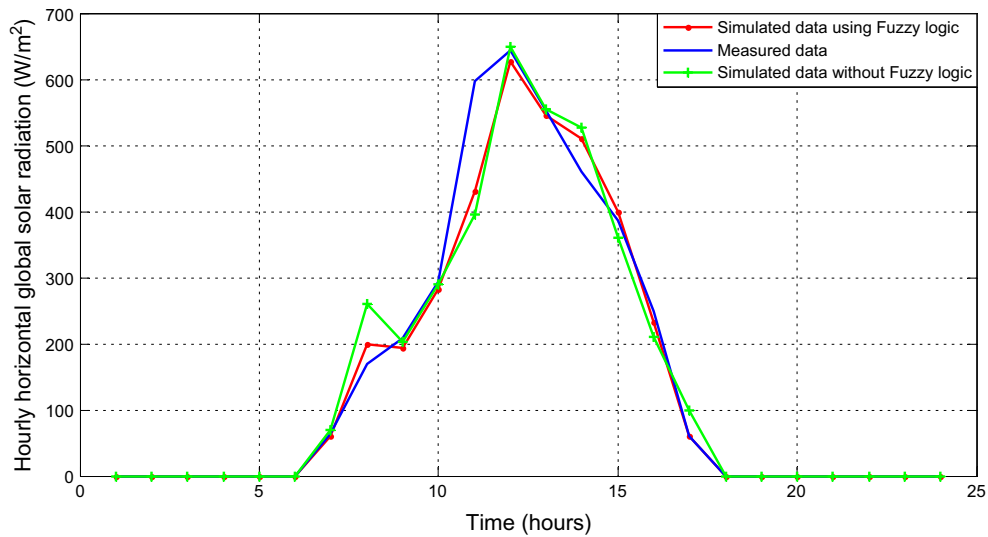


**Fig. 8.** Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 15th February 2011 for the site of Almeria, Spain.

The second step consists in identifying the failures in the storage unit (battery) as failures related to the internal resistance and the overcharging. We indicate that the lead–acid battery works in floating mode between 90% and 100% of state of charge (SOC).

#### 4.1. PV system battery without faults

To check the failures in the PV system battery we used one sunny day for one location to realize our tests. For that, we have chosen the 5th June 2012 for the location of Ghardaia in Algeria. The GISTEL method supplies the PV array by the solar radiation requirements. The output of the PV array is connected to the storage unit and to the variable load. The storage part is used to feed the load at any time of the day. Hence, it is necessary to assure a good performance of the batteries. A good checking of battery means a long lifetime and little period of maintenance that leads to optimize the cost of PV systems. A PV system battery especially lead–acid type needs a special treatment and control of water level. In other hand, the simulation

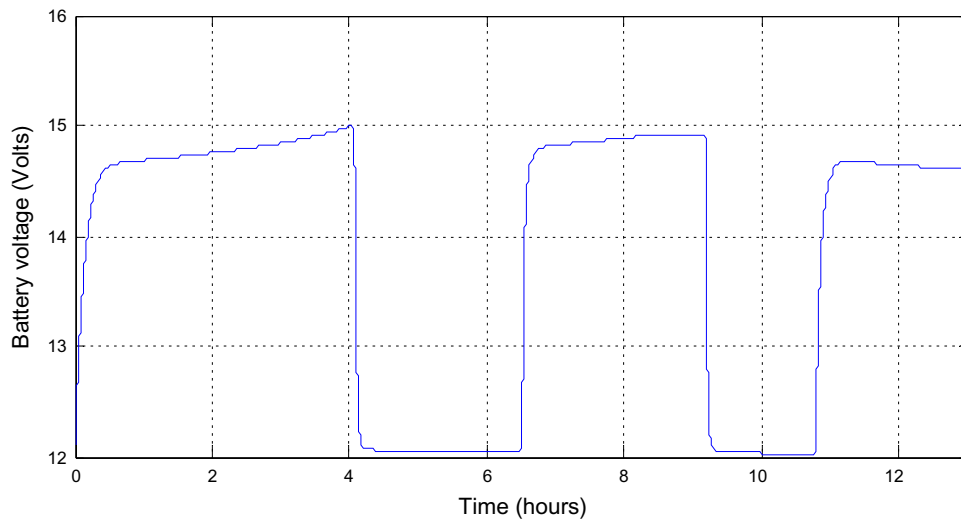


**Fig. 9.** Measured and simulated of the hourly global horizontal solar radiation with FL and without FL method for the day of 20th February 2011 for the site of Almeria, Spain.

**Table 2**

The RMSE and NRMSE between actual data and simulated data with and without fuzzy logic method (FL) method.

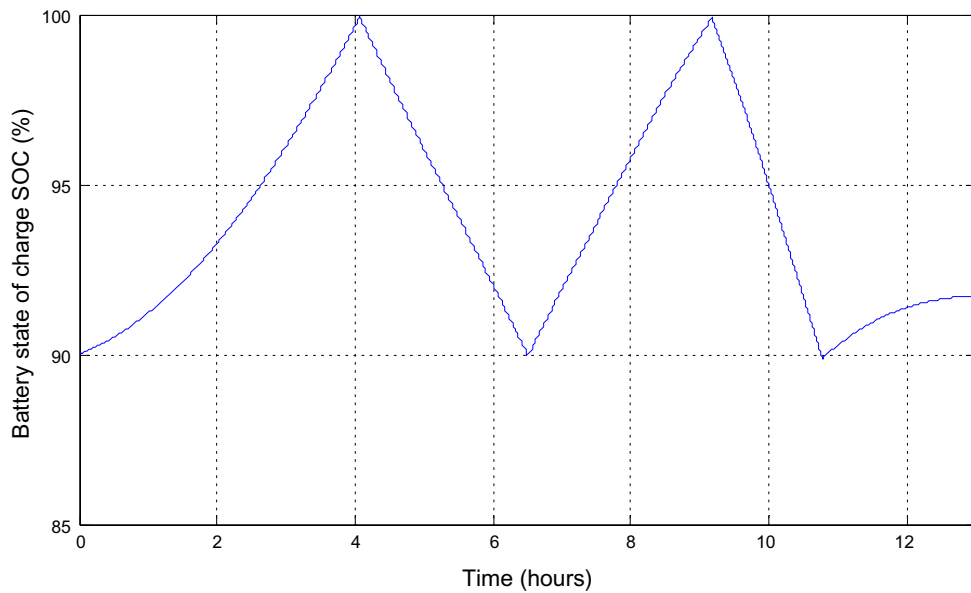
|                       | Date             | Error (RMSE) |            | Error (NRMSE) |            |
|-----------------------|------------------|--------------|------------|---------------|------------|
|                       |                  | With FL      | Without FL | With FL       | Without FL |
| Bouzerreaha (Algeria) | 26 March 2013    | 52.8788      | 69.8051    | 0.2185        | 0.2885     |
|                       | 03 April 2013    | 52.9886      | 63.6144    | 0.2072        | 0.2488     |
| Ghardaia (Algeria)    | 22 November 2012 | 53.8455      | 69.9921    | 0.2285        | 0.2981     |
|                       | 07 December 2012 | 54.2156      | 64.3654    | 0.2181        | 0.2584     |
| Almeria (Spain)       | 15 February 2011 | 23.3158      | 25.5123    | 0.2852        | 0.3121     |
|                       | 20 February 2011 | 36.9515      | 49.0828    | 0.2407        | 0.3197     |



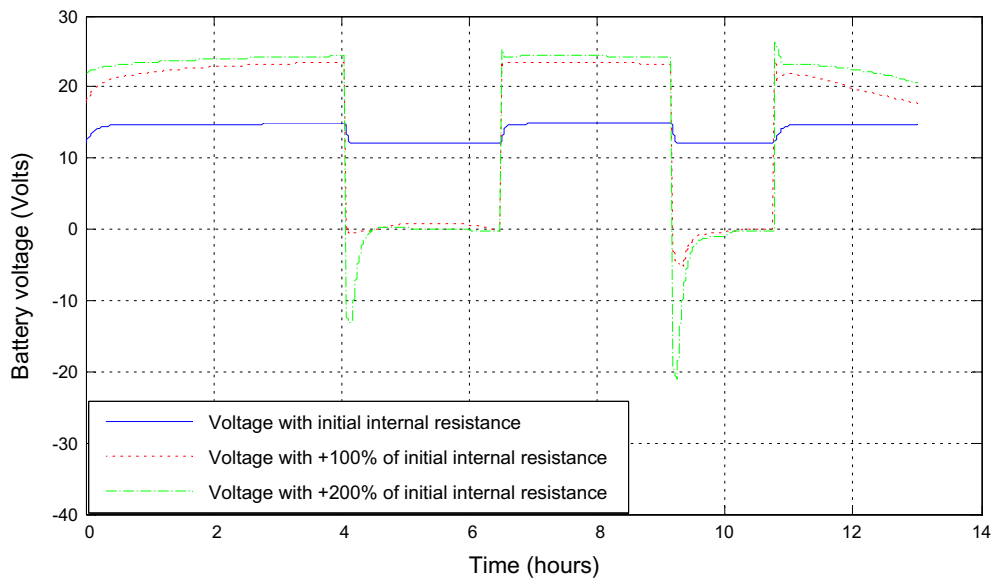
**Fig. 10.** Lead-acid battery voltage.

results of a PV system battery without faults are considered as a reference for the other simulation results. For that, Fig. 10 represents the battery voltage fixed at 15 V the maximum value and Fig. 11 represents the battery state of charge (SOC) without any faults.





**Fig. 11.** Lead-acid battery state of charge (SOC).



**Fig. 12.** Lead-acid battery voltage with different internal resistance values.

From Fig. 10 the battery voltage during charge mode does not exceed the fixed value 15 V for all tested cycles. But in the last cycle, the voltage was decreased depending on solar radiation at the sunset. We suppose it as an ideal curve or a reference result of a sunny typical day.

Fig. 11 explains the state of charge (SOC) of the PV system battery with two and half cycles that used for testing the battery performances. The first cycle was slowly charged due to the small values of solar radiation (case of the sunrise). The same effect was occurred at the sunset period (the battery in the charging mode was slowly increased).

#### 4.2. The effect of the internal resistance in the PV system battery

In this stage, we have used two different values of the battery's internal resistance for checking the effect of the internal resistance in the behavior of the PV system battery. Hence, we have increased firstly the internal resistance of the PV system battery that equals to 1 Ohm by +100% of its initial value and secondly, by +200% of its ideal value.

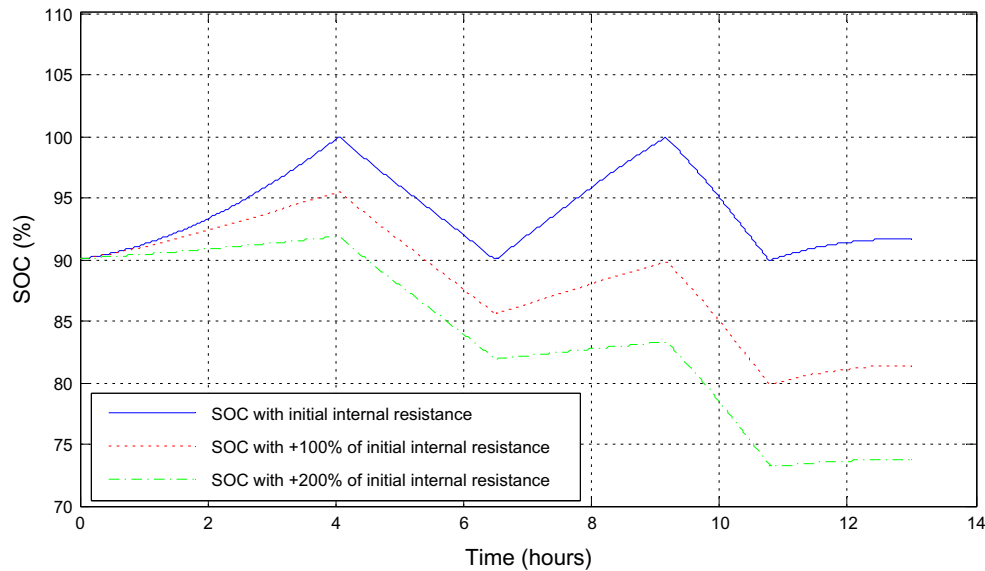


Fig. 13. Lead-acid battery state of charge (SOC) with different internal resistance values.

Fig. 12 represents the battery voltage under different values of the internal resistance, the blue line is the battery voltage at the initial internal resistance; the red line explains the voltage result under +100% of the initial value of the battery's internal resistance and the green line one represents the battery voltage output introduces +200% of the ideal internal resistance. We observed a big exceed in voltage at charge and discharge cases due to the increasing of the battery's internal resistance. An augmentation of the internal resistance with +100% gives high voltage than the initial voltage values. Moreover, the increasing of the internal resistances with +200% gives more voltage than the first case. Hence, and depending on Ohm's law, each increasing of the internal resistance of the battery lead us to an increase of the battery voltage.

Fig. 13 explains the SOC of the solar battery, when the blue curve is the SOC with the ordinary value of internal resistance, the red line represents the SOC cycles with +100% of initial worth of internal resistance and the green line is the SOC with +200% of ideal value of battery's internal resistance. The simulation results have the some input of the solar radiation (GISTEL the satellite method) but the effect of the battery's internal resistance prevented the curves to follow the references. The battery's internal resistance effect has a negative impact on the PV system efficiency. For that; it should be respect the maintenance period and well monitored the storage unit.

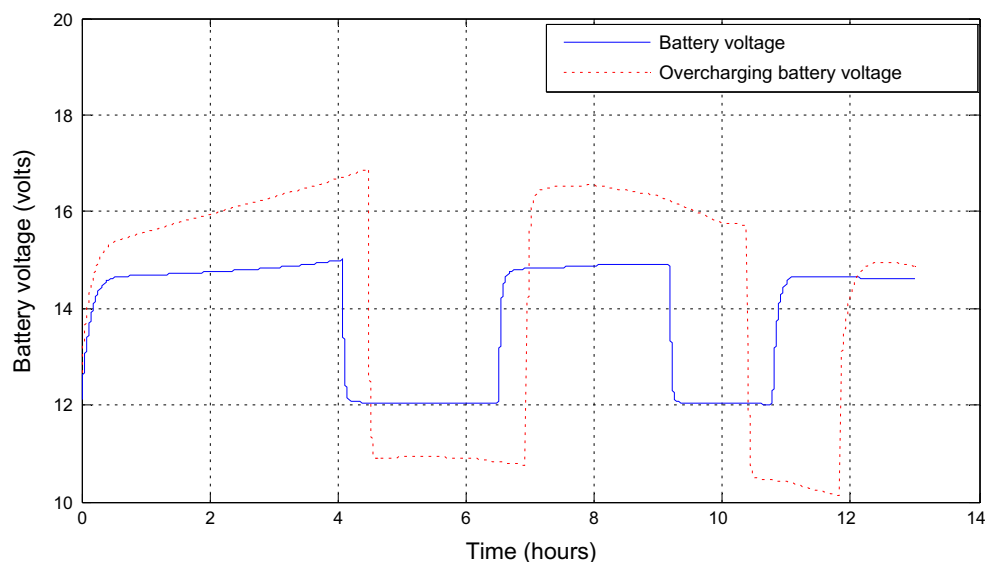
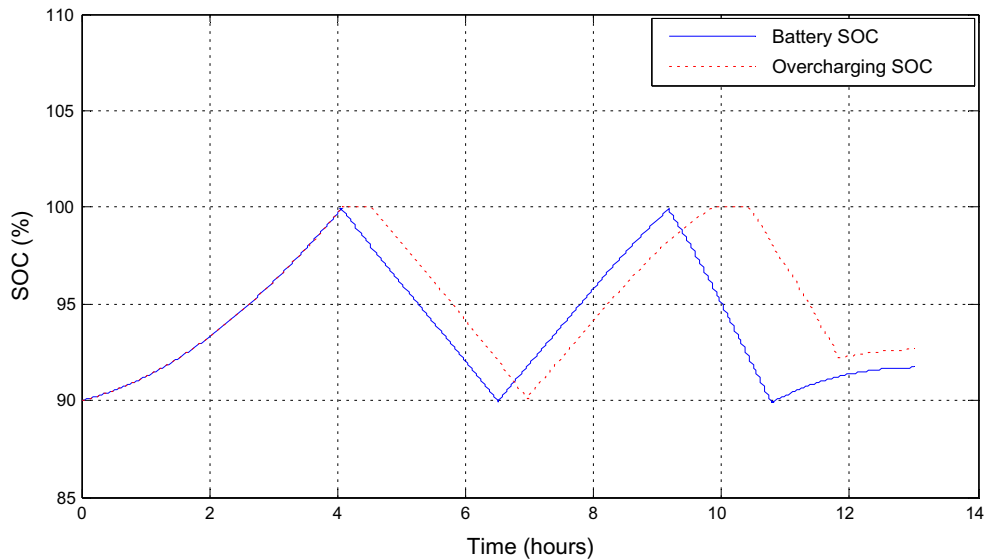


Fig. 14. Lead-acid battery voltage with under overcharging effect.



**Fig. 15.** Lead-acid battery state of charge (SOC) under overcharging effect.

#### 4.3. The effect of the overcharging in the PV system battery

In order to show the negative impact of overcharging in the battery lifetime, we studied the behavior of battery after it is fully charged (arrived at the maximum point of SOC and voltage).

Fig. 14 represents the battery voltage under overcharging effect. The blue line is the battery voltage without any effect that means the reference curve, and the red line is the voltage under overcharging impact. The overcharging effect caused a gap in the allure of the voltage (red line) compared with the reference curve (blue line). These results show a very big degradation at the level of the battery construction that effects its life time.

In addition, Fig. 15 shows the curves of the SOC of the solar battery under the overcharging effect. The blue line is the ideal allure of SOC, and the red one represents the SOC curve under overcharging impact. From this figure, we note a gap between the reference curve and the curve under overcharge effect that causes a decreasing in the level of water in the PV system battery. Hence, the operator should be careful about the occurrence of this problem which results the degradation at the internal plates of the lead-acid battery. For that, the monitoring part is an important task to assure the PV system lifetime planned by the constructor.

## 5. Conclusion

In this paper, we proposed an approach for identifying the losses in the photovoltaic systems batteries, based on checking the lead-acid battery through the estimation of the solar radiation. The methodology used in this work consists, firstly on the estimation of the hourly global solar radiation data using an improved GISTEL model. The objective of this approach is to process the visible satellite images by calculating the transmission coefficients for each pixel of the image. A comparison between those coefficients and the ones obtained from the clear, partial and totally cloudy sky has been achieved; this allows determining the clearness index that is used for the estimation of the hourly global solar radiation. In addition, a combination of the base GISTEL model and a FL technic was used in this model in order to obtain more precise results. At the second stage, we have tested the battery to check the losses in the PV system. Hence, we review our work to study the internal resistances and the overcharging effects in the PV system battery. The detection of the battery faults guaranteed the PV system efficiency. Moreover, combining the estimation of the solar radiation by GISTEL model as the PV system input with the battery checking operation represents a good improvement in the case of a PV systems monitoring. The obtained experimental results showed the accuracy of this approach. In addition, the proposed method does not need a complicate calculation and is based on a few input parameters only.

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